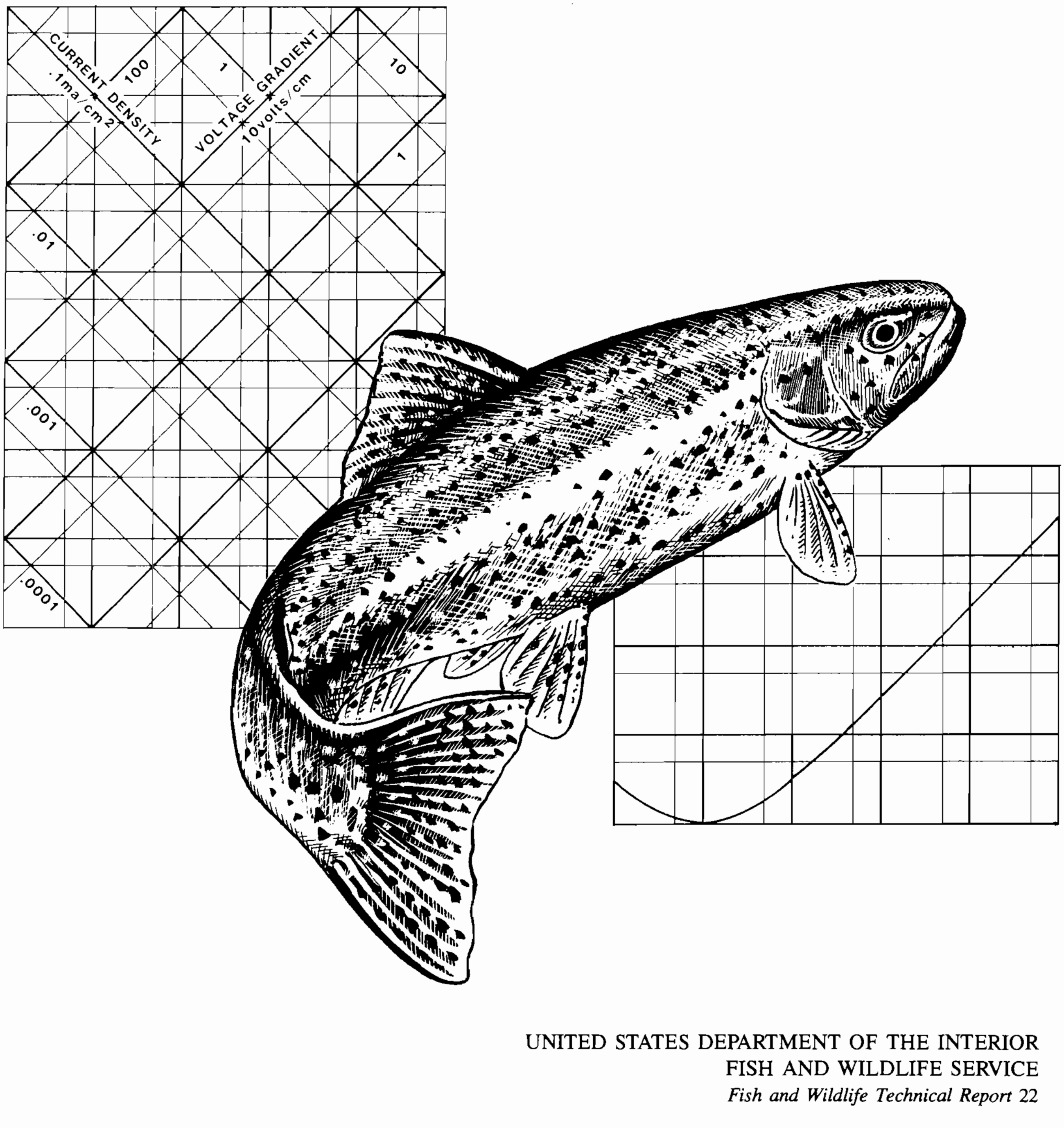
Electrofishing, A Power Related Phenomenon



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A Power Transfer Theory for Electrofishing

by

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Abstract

Electrical terminology and theory are presented as a primer for the introduction of concepts relating power transfer to the principles of electrofishing. Electrofishing is considered effective only when the power transferred from the water to the fish is sufficient to elicit the desired electroshock response. The efficiency of the power transfer depends on the ratio of the electrical conductivity of the water to the "effective" conductivity of the fish. Power transfer is total when the conductivity of the water and fish are equal; all other relations between the conductivities are inefficient. *Power density* is introduced as the definitive term for describing the intensity of electroshock effects. Power density relations are derived and graphic techniques are presented in terms of voltage gradient, current density, and electrical conductivity. The concept of constant power transfer is introduced under the assumption that distinct thresholds of electroshock response are displayed by fish in electrified water and that these thresholds are determined by the magnitude of the power density transferred into the fish. I suggest that these thresholds of in vivo power density are constant and independent of water conductivity.

Electrofishing has gained prominence in recent years as a method for the capture and control of fish in research. Investigators involved with the development of electrofishing techniques must apply interdisciplinary principles that relate electrical theory, water quality, mathematics, and fish physiology and behavior. The bioelectronic aspects of electrofishing have been described by a variety of electrical measurements (Monan and Engstrom 1962; Sternin et al. 1972; Edwards and Higgins 1973). In general, there is a continuing search for an electrophysiological model that adequately predicts the electroshock response of fish. The best measurement of effectiveness in electrofishing does not seem to be among the common electrical terms of voltage, current, resistance, or power.

I present a new approach for understanding the basics of electrofishing principles by applying the electrical theory for power transfer in association with a volumetric measurement of power: *power density*. This concept is new to most fishery biologists who use electrofishing equipment, and no instruments are available to directly measure power density; however, I describe the equations and a graphics method for calculating it. Power density may be the measurement that electrofishing personnel have been seeking in order to adequately understand their field observations.

My hypothesis is that all animals control their muscular action through neural responses that are at least partly electrical. In fact, physiologists commonly determine the activity of nerve cells by Fourier power analysis of electroencephalograms (Turbes et al. 1976). Furthermore, I suggest that neural responses are induced by power levels that are independent of whether the animal is in air or water. To produce an electroshock response, one must only induce in the animal an electrical signal of sufficient power to trigger, interfere with, block, or control the inherent neural responses. Thus, I here consider electroshock to be an electrical power interference phenomenon. This concept can be tested by measuring the electrical power thresholds needed to create specific degrees of electroshock response. For example, operators of electrofishing equipment routinely observe such responses as fright, taxis, and tetany, which can be interpreted to represent discrete thresholds of signal interference with the neural responses. On the basis of the aforementioned tenets, users of electrofishing equipment need to understand how electrical power is transferred into a fish; I here offer a power theory.

I provide to users and designers of electroshocking equipment the terminology and theory necessary to explain electroshocking principles as related to the concepts of power density and power transfer. The electrical theory is developed step-by-step from an elementary base. It is recognized that electrofishing is an unusual technique in which power is remotely applied through a conductive medium to a swimming organism, and that there are no other comparable applications.

Basic Electrical Theory

Many electrical circuits are designed to transfer energy to electrical loads such as lights, motors, and radios. Electrofishing is a unique example of energy transfer to an animal. The concept of energy transfer can be adequately described here with a circuit having a single power source and a single load (Fig. 1). Only direct current (DC) circuits are discussed, but the basic theory applies equally to alternating current (AC) and pulsed direct current (PDC) systems. Some of the explanations that follow have been greatly simplified, but the concepts are still considered useful for the understanding of electrofishing. A glossary of electrical terms is given in the Appendix.

Electrical Charge, Voltage, and Current

Two types of electrical charges are identified in all materials. Early physicists arbitrarily defined one type of charge as negative ($-$) and the other as positive ($+$). When placed in proximity, charged particles generate forces; like charges repel and opposite charges attract. Three distinct charged particles are normally associated with electrofishing: electrons ($-$), positive ions ($+$), and negative ions ($-$). Electrons are the dominant particles in the wired circuits; ions are the active particles in water. Electrical charge is measured in coulombs, but it is more appropriate here to use other electrical terms—voltage or current—that associate the quantity of electrical charge with energy or time.

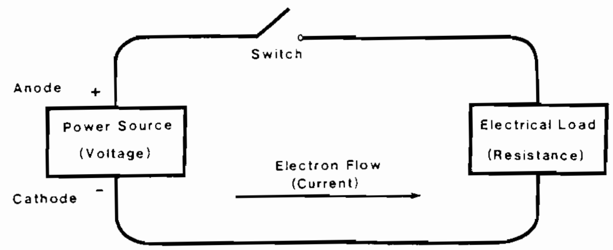

Fig. 1. Basic electrical circuit: One source and one load.

All sources of electrical energy cause a separation of electrical charge ($+$ and $-$) and create a positive charge at one terminal, the anode, and a negative charge at a second terminal, the cathode, as shown in Fig. 1. In the process of charge separation, potential energy is inherently stored on the charged particles. This potential energy can be transformed into other forms of energy such as heat, light, or mechanical motion when the charged particles recombine and neutralize their electrical effects in an electrical load.

The available potential energy is commonly associated with electrical charge through the terms of voltage and volts. A volt (V) is defined as the amount of potential energy stored in each coulomb of charge. Therefore, the higher the voltage, the greater the amount of energy available for transfer to a load. A common misconception is that voltage is a force that pushes the electrical charge through a circuit. But voltage does not create a force; rather, the number of volts is a measure of the potential energy in a circuit. In water, voltage effects are instantly created (at the speed of light) to their maximum intensities when the circuits are activated.

The movement of electrical charge is usually monitored on electroshocking equipment with a current meter. Current (I) is the quantity of charge moving through a circuit per unit of time. Ampere (A) is the common name for current, but the actual units are coulombs per second. Current meters or ammeters are indicators of charge movement and are usually wired directly into a circuit so that the electrical charge passes through the instrument. On the other hand, voltmeters are simply placed across an electrical load or source without disrupting the circuit wiring.

Ohm's Law and Resistance

The forces of attraction and repulsion shown by charged particles result in current flow through the electrical load (Fig. 1). For most applications (electrofishing included), the ratio of volts (V) to current (I) is a constant value called the electrical resistance (R).

$$R = V/I = \text{resistance of a particular circuit} \quad (1)$$

This equation, the familiar Ohm's Law, is a mathematical expression of a physical phenomenon. The unit of resistance is the ohm. Resistance can be considered as a circuit characteristic that expresses an effect opposing the flow of electrical charge and causes a nonreversible transformation of electrical energy into some other form of energy. It is realistic for electrofishing applications to consider the resistance of water to be the frictional opposition of the water medium to the charged ions. Water resistance effectively removes potential energy from the electrical charge and converts it to heat. Although few fishery biologists recognize their elaborate electrofishers as water heaters, heat accounts for most of the energy conversion.

The reciprocal of resistance (R) is conductance (G), which is known by two synonymous units of measurement: mhos or siemens.

$$\text{Conductance (G)} = 1/R \text{ mhos or siemens} \quad (2)$$

Ohm's Law states that resistance for most circuits conforms to a linear relation between volts and current; however, the law provides no insight into what physically composes the resistance. Actually, resistance (as known through Ohm's Law) is only an indirect indicator of the relative freedom with which carriers of electrical charges move through a substance. There is, however, an electrical characteristic that directly measures the freedom of charge movement, called electrical conductivity (not to be confused with conductance). In fact, physics handbooks provide comprehensive tables listing the electrical conductivities for most materials in units of mhos per centimeter or siemens per centimeter. The reciprocal of conductivity (c) is known as resistivity (r). Conductivity meters, which measure the conductivity of water, should be standard equipment for all electrofishing because conductivity may vary by several orders of magnitude in different waters.

The total electrical resistance required in Ohm's Law for any three-dimensional substance involves both the physical dimensions and electrical conductivity of the substance as given by the following equation (Corcoran 1954):

$$\text{Total resistance (R)} = d/(cX) \text{ ohms} \quad (3)$$

where d = length of material, c = conductivity of material, and X = cross-sectional area of material.

As a general rule, biologists can apply Ohm's Law to perform circuit and power analyses, but studies involving electrical transmission in water require equation 3 (which is discussed in further detail later).

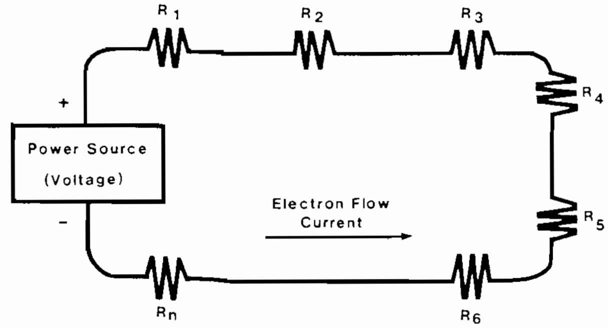

Fig. 2. Multiple electrical loads wired in series.

Electrical Loads Connected in Series

Combinations of electrical loads are often connected to a single power source. One such circuit is the series connection (Fig. 2), where the electrical loads are placed one after another. Christmas tree lights are often wired in series because this configuration requires the least electrical wire. Figure 2 displays the common graphic symbols for each electrical load and denotes each load by R_n. In a series circuit, the same magnitude of current must flow through each load, because the movement of an electrical charge is continuous. In other words, the electrical charge leaving a power source cannot be arbitrarily created or lost as it moves through a circuit. However, the quantity of energy dissipated in each respective load can vary, and consequently different voltages can be developed across the individual loads. The larger resistance values always measure a higher voltage in a series circuit—an indication that these loads dissipate more of the electrical energy.

It is often convenient to calculate a single value of resistance that requires the same current from the electrical source as the string of series resistors. The value of this single resistor (R_T) is the sum of the individual series resistors in ohms. That is,

$$R_T = R_1 + R_2 + \ \ldots \ + R_n \text{ ohms.} \quad (4)$$

The current (I) in a series circuit can be calculated by substituting equation 4 into Ohm's Law, or

$$I = V/R_T \text{ amperes.} \quad (5)$$

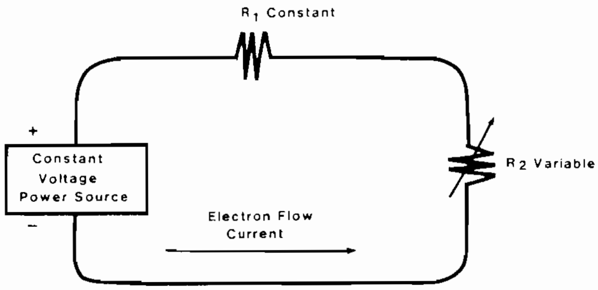

Fig. 3. Constant voltage source driving two electrical loads in series.

The volts across a particular load are

$$V_n = I \times R_n. \tag{6}$$

Power Relations

Power (P) is defined as the energy per unit of time, and the equation for electrical power is easily derived from the definitions of volts and current: The multiplication of volts (V) by current (I) results in power. Thus,

$$\text{Power (energy/s)} = \text{V (energy/charge)} \times \text{I (charge/s)}. \tag{7}$$

The electrical unit of power is the watt (W), where 1 watt = 1 volt × 1 ampere. Ohm's Law can now be substituted into equation 7 to derive two additional power equations related through resistance:

$$\text{Power} = V^2/R \text{ watts} \tag{8}$$

and

$$\text{Power} = I^2 \times R \text{ watts}. \tag{9}$$

Equation 9 is the power relation known as Joule's Law.

Maximum Power Transfer Related Through Circuit Theory

I believe that the effects of electroshock are power related; thus, electrical power must be transferred to any fish captured by electrofishing. The concept of power transfer to a fish is developed here from two approaches: circuit theory and electrical wave theory. The circuit theory is more easily understood, but wave theory better describes the electrical conditions that exist at the interface between the water and the fish.

First, if one considers the electrical circuit of Fig. 3, where a single power source drives two electrical loads connected in series, one of the electrical loads (R_1) is held at a constant value while the second load (R_2) is changed. The question is asked: With the voltage of the power supply held constant, what must be the relative values of the two loads to transfer maximum power to load R_2?

To answer this question, one must calculate the current by equation 5,

$$I = V/(R_1+R_2) \text{ amperes}. \tag{10}$$

The electrical power delivered to the load R_2 can now be calculated by applying Joule's Law (equation 9).

$$\text{Power (to } R_2) = [V/(R_1+R_2)]^2 \times R_2 \tag{11}$$

Equation 11 is rewritten,

$$\text{Power (to } R_2) = qV^2/[R_1(1+q)^2] \tag{12}$$

$$\text{where } q = R_2/R_1 = \text{mismatch ratio}. \tag{13}$$

The maximum value of equation 12 can be determined by graphing the function or applying calculus: The peak of the curve is at $q = 1$. Thus, the maximum available power (P_M) can be obtained from this series circuit (Fig. 3) only when the two ohmic loads are equal. When $q = 1$, the maximum available power is

$$P_M = V^2/(4 \times R_M) \tag{14}$$

$$\text{where } R_M = R_1 = R_2. \tag{15}$$

This concern about power transfer is unusual and unnecessary for most electrical applications. Household appliances, lights, motors, etc. are designed to operate at a particular voltage, and the devices are simply plugged into the appropriate receptacle. One must now consider what might happen if a 1,000-W heater were wired in series with a 60-W lamp. This wiring would obviously create a problem, and neither appliance would function properly. This same problem develops in electrofishing: the water separates the power source from the fish, and the fish is the electrical load to which power is to be delivered. Consequently, fishery biologists concerned with electrofishing must develop an understanding of power transfer theory.

It is convenient to calculate the percentage of maximum power delivered to a load for arbitrary mismatch ratios. A normalized relation for this percentage is easily derived by dividing equation 12 by equation 14.

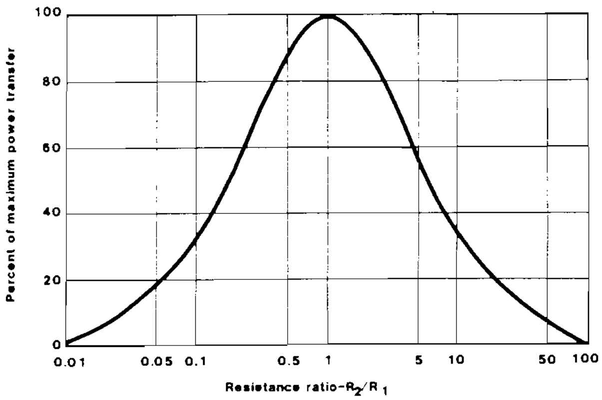

Fig. 4. Normalized maximum power transfer curve.

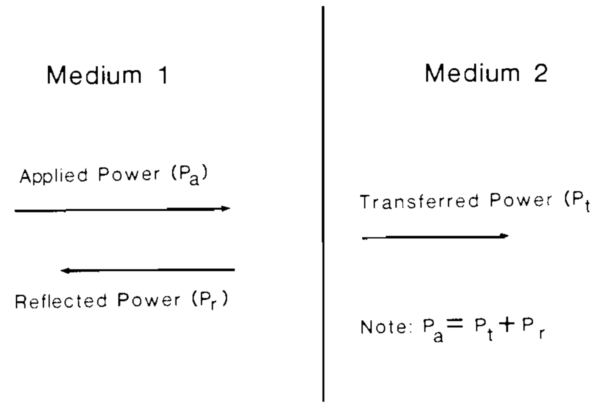

Fig. 5. Wave model for electrical power flow at boundary between two media.

$$\text{Normalized power (\%)} = P(\text{to load})/P_M$$

$$= [4q/(1+q)^2] \times 100 \qquad (16)$$

The graph of equation 15 (Fig. 4) clearly indicates a maximum of power transfer when $R_1 = R_2$. As applied to electrofishing, maximum power is transferred to the fish when the fish manifests a resistive component equal to that of the water. Although resistances of both the water and the fish are not controlled, the concept of maximum power transfer demonstrates a basic electrical principle that affects the transfer of power into the body of a fish.

Obviously, the circuit derivation for maximum power transfer is not a rigorous or adequate model for electrofishing, but it is enlightening. First, water is a resistive component between every electrofishing power source and the fish; second, the purpose of electrofishing equipment is to transfer power to fish. The fish is the desired electrical load, but the water between the electroshocker and the fish must be bridged.

Maximum Power Transfer as Related to Wave Theory

A second perspective to maximum power transfer involves describing what happens to a propagating wave of electrical energy as it impinges on the boundary between two media having different electrical conductivities. The wave model for energy propagation (Fig. 5) is three dimensional and not restricted to wired circuits as previously used to conceptualize maximum power transfer. In the wave model, it is recognized that applied energy is either totally or partly transferred into the second medium or totally or partly reflected back into the first medium (Terman 1955). Thus, three boundary conditions must be satisfied:

$$V_a = V_t + V_r \qquad (17)$$

$$I_a = I_t - I_r \qquad (18)$$

$$P_a = P_t + P_r. \qquad (19)$$

These equations simply state that the voltage (V), current (I), and power (P) of the applied (a) electrical energy must be equal to the sum of the voltage, current, and power that is represented in the reflected energy (r) and transferred energy (t). The negative sign in equation 18 indicates that the reflected current is flowing in the opposite direction relative to the applied current. The goal is to derive a relation showing what portion of the applied power is transferred to the second medium when the conductivities of both media are known.

In any material conducting an electrical charge, the ratio of volts to current must equal the resistance of the medium (Ohm's Law). The resistance of a medium is given by equation 3 when the conductivity is known for the material. Thus, both the applied and reflected waves in Fig. 5 are passing through a resistance value determined by the conductivity of medium 1 (the water) and the transferred wave travels through a different resistive value as set by the conductivity of medium 2 (the fish). Hence,

$$R_1 \text{ (the water)} = V_a/I_a$$

$$= V_r/I_r \qquad (20)$$

and

$$R_2 \text{ (the fish)} = V_t/I_t. \qquad (21)$$

The application of equations 17, 18, and 21 yields

$$V_t = V_a - V_r = I_t \times R_2$$

$$= (I_a + I_r) \times R_2$$

$$= [(V_a/R_a) + (V_r/R_r)] \times R_2 \quad (22)$$

and a rearrangement of terms yields

$$V_r/V_a = (R_1 - R_2)/(R_1 + R_2)$$

$$= (1-q)/(1+q) \quad (23)$$

where q is again the mismatch ratio, as in equation 13.

Equation 23 shows the ratio between the reflected and applied voltages. It must now be recognized that the power in any medium (resistance considered constant) is always proportional to the square of the volts (equation 8). Thus, the ratio of reflected power to applied power must be proportional to the square of equation 23 (Ramo and Whinnery 1953):

$$P/P_a = [V_r/V_a]^2 = [(1-q)/(1+q)]^2. \quad (24)$$

Now equation 19 is expressed as

$$P_t/P_a = [1-(P_r/P_a)] \quad (25)$$

which can be written in terms of q by substituting equation 24

$$P_t/P_a = 4q/(1+q)^2. \quad (26)$$

Equations 16 and 26 can now be compared with the conclusion that power transfer from one medium to a second medium, under the conditions of propagating electrical energy, seems to be analogous to the circuit analysis where P_t corresponds to the power in R_2 and P_a corresponds to P_M at the interface of the media. Thus the same power transfer criterion evolves, whether the solution is approached with circuit theory or with electrical wave theory.

It is likely that some engineers would take exception to this simple use of circuit analysis and wave theory to describe electrofishing. Certainly, fish are not directly wired, as implied in the circuit approach—nor do they present an infinite and uniform boundary, as implied in the wave theory. Although power transfer into a fish is extremely complicated, the results from these simple electrical models provide useful information. The fact that the mismatch ratio is shown as the determining factor for power transfer in both theories cannot be ignored. It should be possible, by using controlled procedures, to verify that fish respond to electrical stimuli in a manner consistent with the tenets of equations 16 and 26.

Inasmuch as the bodies of fish are complex structures composed of electrically dissimilar tissues and fluids, I suggest that the effects of electroshock may be more reasonably studied by measurement methods external to the fish. The technique proposed here evolves from the common engineering practice of reducing complex circuits to single resistance values—the "black box" approach. This notion is here extended to measure a single "effective conductivity" for a fish and ignore the internal body complexities. The electrical model is thereby reduced to two values of conductivity—one for the fish and one for the water. In fact, the absolute values of conductivities for the individual body parts may not be appropriate for studies of electroshock response. The only sound method for evaluating electroshock is to observe the response and behavior of fish in the presence of electrical fields. Marine biologists have used these principles to measure voltage gradient thresholds for various saltwater fishes (Klima 1974).

Power relations as applied to electrofishing are emphasized here, but it is appropriate to mention that similar power concepts are proposed for the design of electric fences (Brockelsby et al. 1977). In fact, in published standards for electric fence controllers (Anonymous 1987), electroshock effects are established at safe levels by specifying the quantity of charge that can be transferred to a load. Manufacturers find it convenient to use a variation of this safety standard and often advertise the output of fence controllers in terms of energy per pulse. This energy designation readily converts to energy per unit of time, which is power. Thus there is a general consistency between the standards accepted for livestock fence controllers and the power concepts proposed here for electrofishing.

Volumetric Variables for Electrofishing

Ohm's Law and the power equations previously described are given in terms of volts, current, and resistance. Most circuit analyses where the charge flow is confined to wires and circuit components (lamps, switches, motors, etc.) are based on these variables. In electrofishing, however, the electrical charge is moving freely through the water in three dimensions, and the electrical terms

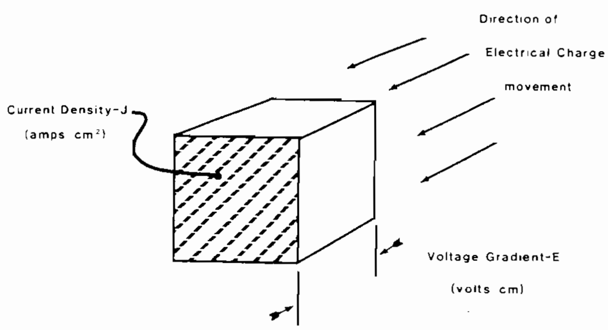

Fig. 6. Volumetric depiction of voltage gradient and current density in a conductive medium.

of volts, current, and power no longer adequately describe the phenomenon. Rather, electrical terms involving length, area, and volume are required. I therefore describe three new variables that are appropriate to electrofishing.

Equation 3 can be used to calculate a resistance value (R) for any conductive medium (having known dimensions), and this equation can be substituted into Ohm's Law. It follows that

$$V = I \times R = I \times [d/(cX)]. \quad (27)$$

Rearranging the terms yields

$$V/d = (1/c) \times (I/X). \quad (28)$$

Now one can define

Voltage gradient (E) = V/d volts per centimeter (29)

and

Current density (J)

= I/X amperes per square centimeter. (30)

Substituting equations 29 and 30 into equation 28 yields a relation known as the second form of Ohm's Law:

$$J = cE. \quad (31)$$

This second form of Ohm's Law enables the measurement of electrical variables relating to charge flow through a three-dimensional medium. In essence, a volume of material (water or fish) is considered as being composed of small cubic volumes. For each cube (Fig. 6), a voltage exists across its length (voltage gradient), and an electrical

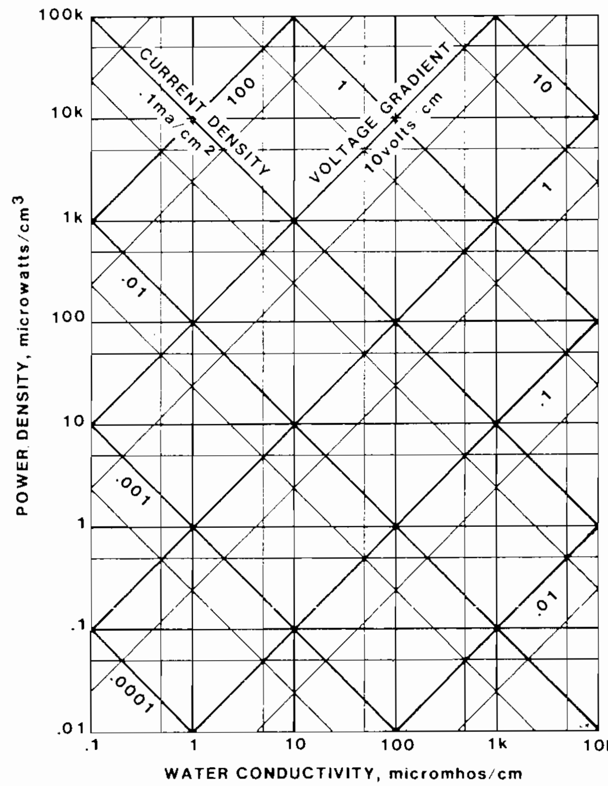

Fig. 7. Relation of power density, water conductivity, voltage gradient, and current density (mA = milliampere; k = 1,000).

charge passes through a surface area (current density). Furthermore, a power term—power density (D)—can be defined to describe the power dissipated per volume; its dimensions are watts per cubic centimeter (W/cm^3). An equation for power density is easily derived from equation 7 by simply noting that each cube has a volume equal to the length of a side (d) raised to the third power (d^3). Thus,

$$D = P/d^3 = (V \times I)/d^3$$

$$= (V/d) \times (I/d^2) = E \times J \ W/cm^3. \quad (32)$$

Following the derivations for equations 8 and 9, two other relations for power density are formed:

$$D = cE^2 \quad (33)$$

$$D = J^2/c. \quad (34)$$

A single graph (Fig. 7) has been developed that simultaneously relates power density, current density, voltage

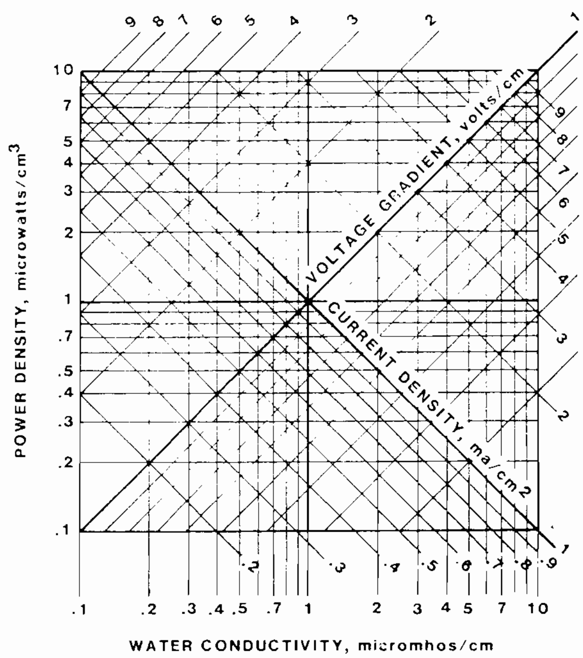

Fig. 8. Expanded power density versus water conductivity (mA = milliampere).

gradient, and conductivity. All four scales on the graph are logarithmic. This graph has proven to be very useful in plotting values of power density versus the observed electroshock response of fish in water of known conductivity. In fact, this graph, when used in conjunction with the principles of maximum power transfer, seems to provide a method for truly understanding the principles of electrofishing.

Experienced biologists will recognize that present instrumentation can readily measure the power delivered to the electrodes by an electrofishing generator, but this power measurement is not by itself indicative of the magnitude of power density present in the water. Consequently, there is a need to develop in-water measurement techniques specifically for electrofishing. Likewise, there are no instruments to measure current density. However, conventional voltmeters and oscilloscopes can be adapted to measure voltage gradient, and the combination of voltage gradient and water conductivity determines power density (equation 33). Current density can also be determined from Fig. 7 or equation 34. Thus, there are indirect methods of calculating these variables for electrofishing applications. For example, if electrofishing is being carried out in water having a measured conductivity of 100 μmhos/cm, and the electrode voltage is adjusted for an in-water gradient of 1 V/cm at the anode, the operator enters the horizontal axis of Fig. 7 at 100 μmhos/cm and traces this conductivity value vertically to its intercept with the diagonal gradient line at 1 V/cm. This intercept determines the corresponding values of power density (100 μW/cm^3 on the ordinate axis) and current density (0.1 mA/cm^2 on the opposite diagonal scale). Thus, every location on Fig. 7 uniquely determines the corresponding values of water conductivity, power density, voltage gradient, and current density. Only two of the four variables are required to enable entry into the graph.

It is useful to observe the cyclical pattern of the power density graph (Fig. 7): alternate decades along both the vertical and horizontal axes repeat. An expanded graph showing four decades (Fig. 8) enhances the resolution and graphic utility.

Power Transfer as Applied to Electrofishing

Conductivity Considerations

The normalized power transfer curve of Fig. 4 indicates how power transfer changes with resistance ratio. This figure also applies if conductivity ratios are known because of the reciprocal relation between resistance and conductivity (equation 3). Thus,

$$q = R_2/R_1 = c_1/c_2. \tag{35}$$

The comparative ease with which biologists can obtain water conductivity readings makes conductivity ratios the preferred terminology. Unfortunately, there are no standardized methods to determine the conductivity of fish, and no substantiated conductivity values are available for fish. This enigma must be resolved through research.

It is appropriate to draw attention to the logarithmic symmetry in Fig. 4 about $q = 1$. This symmetry causes every value of q and its reciprocal to have the same normalized power transfer. Thus, the normalized power curve may be entered with little regard about whether q has been inverted (c_1/c_2 or c_2/c_1), because the same power transfer results.

Concept of Constant Power

The normalized curve (Fig. 4) was derived under the assumption of a constant circuit voltage; however, electrofishing equipment is normally operated with a variable voltage, and this adjustment allows the system's applied power (P_a) to be increased or decreased. This control of P_a also varies the amount of power transferred (P_t). Obviously, if full voltage control were available, any finite load could be driven to any desired power level, regardless of the mismatch.

The question now asked is, "How must a system's applied power be manipulated to ensure that the transferred power (P_t), under conditions of mismatch, remains constant and equal to the power delivered under matched conditions (i.e., $P_t = P_M$)?" The answer is available from the normalized curve (Fig. 4). The factor by which a system's applied power must be multiplied is determined by a function that is exactly the reciprocal of the equation for normalized power (equation 26). This relation is a result of the product of any function and its reciprocal being unity, which here represents the constant transfer of power. This power multiplier is arbitrarily named the multiplier for constant power (MCP). Figure 9 shows the curve of this normalized power multiplier, given by

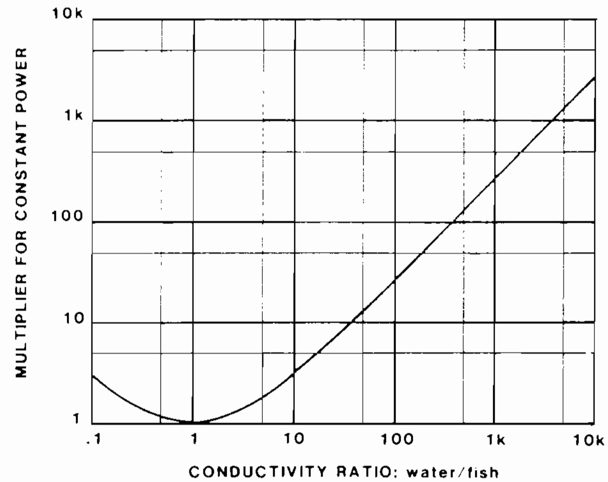

Fig. 9. Normalized curve for predicting the increase in power needed to maintain a constant transfer of power at different conductivity ratios (k = 1,000).

Multiplier for constant power (MCP)

$$= P_a/P_m = (1+q)^2/4q. \quad (36)$$

In this equation, P_M is replaced by P_m to emphasize the inverted relation between equations 26 and 36; that is, the power transfer curve displays a maximum and the MCP expresses a minimum, and the product of the two curves is unity for all conductivity ratios when $P_M = P_m$ = the desired constant value of transferred power. It is useful to interpret P_m as the minimum or threshold of transferred power desired under all conditions of mismatch.

Power or Power Density Versus Electroshock Response

The power multiplier indicates how a system's applied power must be increased (through voltage control) to maintain a matched equivalent power ($P_M = P_m$) into a mismatched load. It should be clarified that there is a one-to-one correspondence between the electrical power delivered into the water and the power density at any arbitrary location in the water. For example, the power density at any location in the water or in the fish increases or decreases by the same percentage as that by which the power applied to the water is increased or decreased. Thus the power multiplier can be used directly in conjunction with the power density graph, and Figs. 7 and 9 are correctly shown at the same scale. With the knowledge that power and power density have a one-to-one relation, it is possible to write equation 36 as

$$D_a/D_m = (1+q)^2/4q \quad (37)$$

where D_a = applied or available power density in water and D_m = magnitude of constant power density to be transferred to fish.

The substitution of equation 35 yields

$$D_a/D_m = 1/2 + 1/4[(c_f/c_w) + (c_w/c_f)] \quad (38)$$

where c_w = conductivity of water and c_f = effective conductivity of the fish.

When equation 38 is plotted on Fig. 7 for selected values of c_f and D_m, the resulting curve conforms exactly to the normalized MCP curve of equation 36 (Fig. 9) with the vertex shifted to the coordinates of c_f and D_m.

Power transfer theory offers new methods for evaluating electrofishing principles and techniques. Figs. 7 and 9 are powerful tools for understanding electrofishing phenomena; biologists are urged to plot their field observations on Fig. 7 for various species and sizes of fish. Standard curve-fitting techniques can be applied to correlate experimental observations against the predicted power density response curve (Fig. 9). Each type of electroshock response (e.g., electrotaxis, tetanus, fright) should be plotted on a separate graph. I believe that the threshold values as determined from these power density plots will conform to the shape of the MCP curve, with some displacement in the vertex position. The coordinates of these displaced vertices are significant: they determine both the threshold of power density required to induce a particular electroshock response under matched conditions (D_m) and the "effective" conductivity of the fish (c_f). Under the concept of constant power transfer, D_m can also be interpreted as the threshold of in vivo power density required to elicit a specific electroshock response from a fish in water of any conductivity. The application of power transfer theory should result in significant advances in the understanding of electrofishing principles.

Suggestions for Research

I have introduced a number of new and divergent concepts about electroshock phenomena as disclosed through power transfer theory. Unfortunately, no immediate values are available for many variables such as fish conductivities, in vivo power density thresholds, and current densities. This lack of information—except for the voltage gradient observations in marine water (Klima 1972, 1974)—has caused electrofishing to be treated as somewhat of an art rather than a science, and in this process the concepts of power transfer have been ignored. I have presented the electrical theory and graphic techniques that I consider necessary to advance electrofishing methodology.

The power transfer concepts presented here must be experimentally evaluated. I suggest that the initial research be based on three assumptions: (1) It is possible through visual observation to identify distinct levels of electroshock response in fish, commonly described as fright, electrotaxis, narcosis, tetanus, etc. (2) Certain thresholds of in vivo power density always elicit a particular electroshock response. These thresholds are independent of water conductivity but definitely depend on fish size and species (Seidel and Klima 1974) and probably on water temperature. (3) Fish respond to electroshock in a manner consistent with the tenets of electrical power transfer.

Application of these three assumptions should yield many possibilities for research; several examples follow.

1. Measure the in vivo power density thresholds for a number of species, using fish of various sizes.
2. Measure the effects of such factors as fish length, body conformation, body orientation relative to the direction of power flow, and size of scales and compare the power density threshold responses.
3. On the basis of power density measurements, determine the effects of electrical waveforms on electrofishing. Compare the electroshock response for AC, DC, and PDC waveforms. How do duty cycle, pulse repetition frequency, and pulse width influence electrofishing efficiency?
4. Develop electrode arrays that optimize the shape of the power density field in the water.
5. Determine the "effective" conductivity for various species of fish and compare size differences.
6. Develop better in-water measurement techniques, and adapt instruments directly for use with electrofishing equipment.
7. Modify electrofishing equipment designs to take full advantage of the knowledge that electroshock effects are power related.
8. Determine the rates of recovery for fish placed in high power density fields for various exposure times.

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Appendix. Glossary of Electrical Terms.

Conductivity (c) The ratio of the density of the unvarying current in a conductor to the voltage gradient that produces it; common units of measurement are mhos per centimeter or siemens per centimeter.

Conductance (G) The measurement of the ability of a component to conduct electricity; the reciprocal of resistance; unit of measurement is the mho.

Current (I) The rate of electrical charge flow in a circuit. The practical unit is the ampere, which is one coulomb per second.

Current density (J) The ratio of a current to the cross-sectional area of its path in a plane perpendicular to the direction of the current.

Effective fish conductivity (c_f) The apparent electrical conductivity of live fish as determined by statistically fitting electroshock response data to the theoretical curve developed for the concept of constant power.

Electrical charge (Q) A fundamental property of matter that can be classified as a fundamental physical quantity. The practical unit is the coulomb. The electron, the smallest charge identified in nature, has a magnitude of 1.6×10^{-19} coulomb.

Mismatch ratio (q) The ratio of either the two resistance values or two conductivity values determined for adjoining media. For electrofishing, this is the ratio of conductivity of the water to the effective conductivity of the fish.

Power (P) The rate of doing work or the energy per unit of time. The practical unit is the watt, which is one joule per second.

Applied power (P_a) Power incident at an electrical interface separating two media.

Constant transferred power (P_m) The constant value of transferred power desired under all conditions of mismatch.

Maximum output power (P_M) The maximum available power delivered to an external load from a power source having an internal resistance equal to that of the external load.

Reflected power (P_r) The portion of applied power that is not transferred to the second medium.

Transferred power (P_t) The portion of applied power transferred from the first medium to the second medium.

Power density (D) The power or energy per unit of time dissipated in a given volume of material; the unit of measurement is watts per cubic centimeter.

Applied power density (D_a) Power density available for transfer to a fish at a particular location in the water.

Power density in fish (D_m) The desired constant value of power density to be transferred to a fish; also, the threshold of in vivo power density required to produce a specific electroshock response.

Resistance (R) The ability to react to the flow of AC or DC with an opposition to the flow of current. Also, the ratio of the applied voltage to the induced current that it produces. The unit of measurement is the ohm.

Resistivity (r) The reciprocal of conductivity. The common unit of measurement is the ohm-cm.

Volts or **Voltage (V)** The energy per unit of electrical charge. The volt is the unit of measure where one volt is one joule per coulomb.

Voltage gradient (E) The rate of change of voltage with distance. Also, the force per unit of electrical charge. The common unit of measurement is volt per centimeter.

Kolz, A. Lawrence. 1989. **A Power Transfer Theory for Electrofishing.** Pages 1–11 *in* Electrofishing, a Power Related Phenomenon. U.S. Fish Wildl. Serv., *Fish Wildl. Tech. Rep.* 22. 24 pp.

Electrofishing effects are created by the electrical power transferred from the water to the fish, and the efficiency of this transfer is shown to depend on the ratio of the electrical conductivity of the water to the ''effective'' conductivity of the fish. Mathematical relations are derived to introduce the concept of constant power transfer. The significance of power density for electrofishing terminology is explained, and graphic techniques are presented in terms of power density, voltage gradient, current density, and electrical conductivity.

Key words: Fish, electricity, power, power density, electrical shock, voltage, current, resistance, conductivity.

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